Turbulence off the Coast of Oregon: A Large-Eddy Simulation Study

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Award #: N00014980113

LONG-TERM GOALS

Our long-range research goal is to improve understanding of small-scale mixing processes in the coastal ocean environment and to incorporate the effects of these processes in coastal ocean models. We will increase the accuracy of coastal mesoscale prediction models by adding physically-based approximations to one-dimensional mixing parameterizations.

OBJECTIVES

Recent studies of the open ocean upper boundary layer using large-eddy simulation (LES) methods have demonstrated the value of these models in describing turbulent processes in the ocean. We are now at a point where LES can be applied to a broader range of problems that include the coastal surface and benthic boundary layers. Our objectives in this work are to determine the accuracy of LES models in coastal flow scenarios, examine the role of turbulent mixing in defining boundary layer structure, and apply observations and LES results to understand and improve commonly applied mixing parameterizations (e.g. Mellor and Yamada 2.5 model and the K profile parameterization). Specific questions we will address include:

- Are Langmuir cells important in inner- and mid-shelf surface layers?
- How do mixing properties (dissipation rates, buoyancy fluxes, surface and bottom boundary layer stresses) vary from one location to another?
- Do the M-Y and KPP mixing schemes predict local turbulent processes in the Oregon shelf?
- What is the role of small-scale bathymetry variations (vertical scale ~O(1-10 m), horizontal scale ~O(10-100 m)), especially in the inner shelf?
- What are the fundamental differences in mixing statistics of M-Y, KPP, LES, and microstructure measurements?

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Turbulence off the Coast of Oregon: A Large-Eddy Simulation Study**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **College of Oceanic and Atmospheric Sciences,,104 Ocean Admin. Bldg.,Oregon State University,,Corvallis,,OR, 97331**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

The central hypothesis of the proposed effort is that improvements in existing parameterizations of turbulent processes require a physical basis and that this basis may be gained through analyses of LES results and turbulence observations. To test this hypothesis, we propose to predict the three-dimensional physical structure of mixing in the coastal environment by conducting a series of experiments using an LES model driven by mesoscale forcing. These model experiments will focus on three main topics:

- Validation of the model using measurements of turbulence structure and evolution.
- Comparison of LES derived turbulence parameters, such as turbulent kinetic energy budget terms, with parameterizations, specifically the M-Y model and KPP.
- Detailed analysis of turbulence in the coastal environment and modification of parameterizations to include new physical insight.

We apply the Ocean Large Eddy Model (OLEM) (Skyllingstad et al. 1999), which is designed to simulate flow encompassing several hundred meters in each horizontal direction and tens of meters in the vertical. The domain is large enough to accommodate the dominant energy containing motions, e.g. Langmuir Circulation, convective rolls, and Kelvin-Helmholtz shear instabilities. In FY01, the model was adapted to a channel domain divided amongst processors in a multiprocessor environment. A domain size of approximately 1440 x 128 grid points in the horizontal direction and 40 points in the vertical was used in this approach with a grid spacing of 1 m. This adaptation allowed for examining the effects of isolated, small scale topographic features, such as ridges and bumps, on the average and tidal flow.

WORK COMPLETED

Both LES and POM Experiments were started concentrating on the bottom boundary layer structure off the Oregon coast. For the LES cases, a typical flow scenario for coastal upwelling was used to examine the turbulent behavior of the bottom boundary layer along with stronger tidal flows. POM simulations focused on a similar coastal domain and tested three mixing parameterizations: KPP, Mellor and Yamada, and K-epsilon. Results from these experiments were reported at the Fall 2000 AGU meeting. Research reported here will be submitted as a peer-reviewed article.

RESULTS

Our focus during the second year of research has centered on the bottom boundary layer structure over topographic features. A key component of this research is determining oceanographic conditions that cause increased drag and mixing by bottom topographic features.

Observations taken during the NOPP 1999 cruise showed that the bottom boundary layer (BBL) is typically O(10 m) deep and is physically separated from the surface boundary layer. The BBL is thought to behave like a wall boundary layer with the southward currents forced during upwelling events and tides providing a source of bottom shear stress. Measurements also indicate regions of stronger turbulence, often detached from the bottom, that cannot be easily explained from the data. In regions of significant variations in bottom depth, such as Stonewall Bank, turbulence has been attributed to the interaction of stratified flow over bottom topography (Nash and Moum 2001). Atmospheric theory (Smith 1985; Bacmeister and Pierrehumbert 1988) suggests that flow interaction with bottom features could generate significant drag on the overlying fluid, along with patches of strong turbulence. In FY01, we performed experiments using LES to determine if a similar process can occur in the coastal environment.

Key parameters that control the strength of drag from bottom obstacles are the stratification as measured by the Brunt Vaisala frequency,

$$N = -\frac{g}{\rho}\frac{\partial \rho}{\partial z}$$, where ρ is the density, g is gravity, and z is the depth,

obstacle height, h, and water velocity, U. Using these parameters to nondimensionalize the obstacle height yields,

$$\hat{h} = hN/U\ .$$

Assuming hydraulic flow conditions, the value of $\hat{h}$ is similar to an inverse Froude number and can be used to diagnose the behavior of the flow. For values of $\hat{h}$ much greater or smaller than 1, the flow is considered subcritical or supercritical, respectively, and is characterized by a symmetric structure above the obstacle and a low drag state. For $\hat{h}$ between ~0.1-0.9, the flow can enter a transitional state with strong acceleration on the downslope section of the obstacle, the formation of a turbulent wake region, and increased obstacle drag. Using Long's equation (Long 1955), Smith (1985) found that only specific values of $\hat{h}$ would yield transitional flows with high drag state conditions. The key to the Smith theory is the formation of a dividing streamline separating the unperturbed flow aloft from the hydraulically controlled flow near the bottom. Smith's solution was tested for an atmospheric case by Bacmeister and Pierrehumbert (1988) using a critical layer as a reflecting surface or dividing streamline height. In the ocean, the critical layer is replaced by the ocean surface so that the depth of the water column becomes an important parameter for determining obstacle drag.

Results from four experiments are presented here that demonstrate the potential for high drag states in the coastal ocean. Initial conditions for these test are based on idealized conditions that are within the realm of actual observations from the 1999 NOPP cruise along the Oregon coastal shelf. Linear temperature and salinity profiles were imposed so that N = 0.025 s^{-1}. Bottom bathymetry was set as an infinite ridge with $h = H/(1 - x/a)^2$, where H = 4.5 m and a = 15 m. Simulations were performed in a channel domain 696 m long, 96 m wide, and 45 m deep with periodic lateral boundary conditions and a grid resolution of 0.75 m.

Three simulations were performed with the above fixed conditions and initial velocities of 0.2, 0.32, and 0.4 m s^{-1}, all assumed to be in geostrophic balance. For each velocity, Smith's solution gives an optimal reflection height (or water depth) of 28, 39, and 50 m for maximum flow transition, indicating that a transition flow is possible when U = 0.32 m s^{-1}, but not when U = 0.2 or 0.4 m s^{-1}. Plots of the flow for U = 0.2 and U = 0.32 m s^{-1} are shown in Figure 1 and tend to support Smith's results. For U = 0.2 m s^{-1}, the flow appears to be subcritical with a lowering of isopycnals above the bottom topographic ridge and weak lee waves downstream from the obstacle. In contrast, when U = 0.4 m s^{-1} the flow is asymmetric with a strong acceleration downstream from the ridge and developing regions of turbulence beneath a lee wave structure.

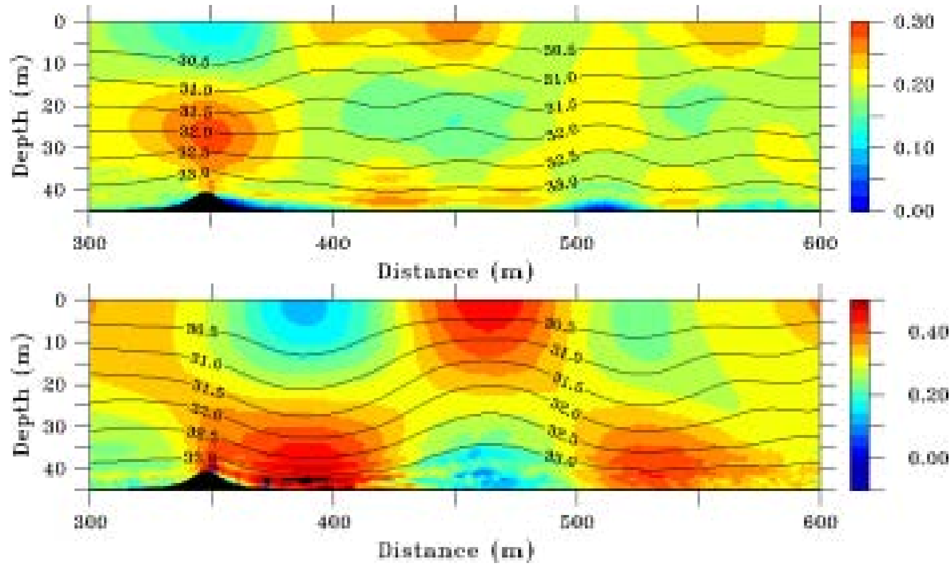

Figure 1. Vertical cross section showing horizontal velocity and salinity for U = 0.2 m s^{-1} (top) and U = 0.32 m s^{-1} (bottom) after 40 minutes simulation time. These plots show how resonant reflection of internal waves off the ocean surface produce much stronger lee waves when U = 0.32 m s^{-1}.

Plots of the depth integrated momentum loss or total drag as a function of time (Figure 2) clearly show the applicability of Smith's solution. When the predicted dividing streamline height is below the model surface, the flow does not produce the characteristic "dead" zone downstream from the obstacle. With higher velocity, the flow becomes supercritical and again does not undergo a transition. Consequently, the drag is not as strong in these cases.

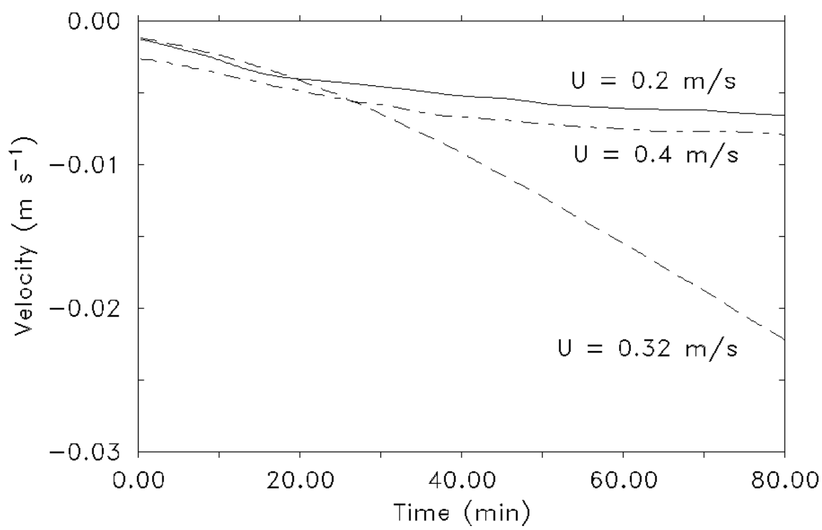

Figure 2. Volume averaged momentum change as a function of time. This plot shows how increased drag from flow separation behind a bottom obstacle is affected by the flow configuration. Transitional flow with U = 0.32 m s^{-1} causes a high drag state, while U magnitudes greater or less than this value do not create as much drag.

IMPACT/APPLICATIONS

In most coastal models, the bottom boundary layer is crudely represented with uniform roughness and no boundary layer model. Our work provides a more solid basis for simulating the effects of bottom roughness variations and interaction with the coastal current structure. Although this research is only a first step in parameterizing bottom roughness effects, our results suggest that parameterization techniques for mountain wave drag applied in atmospheric models may be adapted to the ocean environment.

TRANSITIONS

Improvements in the turbulence parameterization models will be incorporated into general purpose versions of POM and made available to the oceanographic community. Results from these experiments will help in planning future experiments on the Oregon shelf using an Autonomous Underwater Vehicle (Wijesekera and Boyd).

RELATED PROJECTS

This work complements efforts in the COAST and Oregon NOPP programs. Both of these projects utilize coastal models that will benefit from improved mixing parameterizations.

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